# Meteorological Studies With the Phased Array Weather Radar and Data Assimilation Using the Ensemble Kalman Filter


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## LONG-TERM GOALS

The long-term goal of this project is to integrate two state-of-the-art technologies, the phased array weather radar (PAR) and the emerging Ensemble Kalman Filter (EnKF) data assimilation method, to optimize the radar performance and improve coastal and marine numerical weather prediction (NWP).

## OBJECTIVES

This project will leverage on the new PAR in Norman, Oklahoma to exploit phased array technology and its applications to improve NWP through EnKF data assimilation with the goal of improving environmental characterization and forecast to optimize naval operation. This project will further enhance the existing collaboration among ONR, National Serve Storms Laboratory (NSSL), and the University of Oklahoma (OU) to achieve the four specific research objectives. (1) develop an EnKF framework for optimally assimilating quantitative observations of the atmosphere including the PAR data, (2) design a sophisticated radar emulator which will be used to validate innovative processing techniques developed in the project and to design accurate and efficient forward observation operators

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for assimilating PAR data, (3) advance phased array radar technology through the development of novel signal processing techniques and integration of current state-of-the-art technologies to provide high-quality and high-resolution weather measurements, and (4) evaluate the impact of scanning strategies including SPY-1 tactical and non-tactical waveforms on data assimilation and NWP using the Observing System Simulation Experiments (OSSE) and Observing System Experiments (OSE). Optimal scanning strategies of PAR for NWP model initialization will be developed and tested.

## APPROACH

Our multidisciplinary team is comprised of scientists with academic and industrial expertise in radar engineering, radar signal processing, EnKF data assimilation, numerical modeling, and weather prediction. Our approach is to exploit these complementary talents to achieve the goals of the proposed research. The five main research thrusts are discussed in the following.

(1) Design of the PAR Emulator: A sophisticated PAR emulator is designed to take in high-resolution three-dimensional meteorological fields and to generate synthetic radar time series data. The output of the emulator is then processed to produce the three spectral moments (reflectivity, mean radial velocity and spectrum width). The emulator is flexible enough to produce radar data for various waveforms, sensitivity, and sectoring. Artifacts such as ground clutter, point target, radar system noise, attenuation, range and velocity folding can also be simulated. The emulator will serve as a vehicle for developing accurate and efficient forward observation operators for PAR data assimilationMoreover, error characterization can be obtained in the emulation and will be fed into the EnKF system.

(2) Establish the EnKF system: The existing EnKF-based OSSE framework for radar data developed by our group will be extended (a) to use much more realistic yet efficient forward observation operators that will be derived from the full-scale PAR emulator discussed in (1), (b) to handle PAR data collected in various non-conventional manner including those used in the SPY-1/TEP (Tactical Environmental Processor), (c) to assimilate cross-beam winds potentially available through spaced antenna (SA) method, and (d) to effectively account for model errors. The availability of an accurate and realistic radar emulator will allow us and the Navy to evaluate the impact of various simplifications (needed for efficient) in the observation operator on the quality of analysis and the subsequent forecast. The varying PAR scanning strategies will require much greater flexibility in the filter code design. Concerted efforts will also be made to parallelize the filter code for distributed memory processors because of the potentially large volume of radar data to assimilate.

(3) Technology Innovation: This research thrust focuses on the exploration of phased array technology merging with novel signal processing techniques to develop optimal scanning strategies. An agile beam phased array radar has the potential not only to increase the scanning rate, but also to measure meteorological variables not currently available and to enhance data quality. Two focus areas are proposed to address these issues. (a) A novel scanning scheme termed beam multiplexing (BMX) is developed to optimize the scan time and data quality. (b) The application of SA method on weather radar to measure the cross-beam wind component will be tested and verified using the PAR emulator. The impact of additional cross-beam wind measurement on numerical prediction will be evaluated and quantified using the OSSE.

(4) Observing System Simulation Experiment (OSSE): A comprehensive simulation system will be designed to integrate the processes of designing radar scanning strategies, making observations,

assimilating data, and producing forecasts with the goal of improving short-term weather prediction and better understanding the relationships among all involved processes. The SPY-1 waveform with 1-pulse (reflectivity only) in clear mode, 3- or 4-pulse in Moving Target Indicator (MTI) mode, 16-pulse, and 32-pulse will be simulated and their impact on data assimilation and weather forecast will be evaluated and quantified. Moreover, a framework for developing an optimal scanning strategy will be established based on a feedback design in the simulation. In other words, the information of the difference between the forecast and high-resolution model outputs can be used to adjust scanning patterns until optimal results are achieved.

(5) Data Collection and Observing System Experiments (OSE): The findings and lessons learned through radar emulator and OSSEs will then be demonstrated using the PAR at NWRT. Various scanning strategies tested with the OSSEs will be implemented with the PAR. We will leverage on a suite of existing weather radars including the research NEXRAD (KOUN), the mobile SMART radars, the nearby operational NEXRAD (KTLX) radar to validate the PAR measurements and retrieved variables.  For example, the two mobile SMART radars will be strategically deployed to perform dual-Doppler analysis to estimate the three-dimensional wind field that can be used to verify the retrieved wind field and transverse wind measured by the SA method. Moreover, the co-located KOUN will be operated simultaneously using conventional scanning pattern in contrast to the irregular but strategic sampling patterns used by the PAR. Observations from these two radars will be assimilated individually using an EnKF which will allow effective assessment and quantification of the impact of PAR sampling strategies, for real weather.

A multidisciplinary team including 6 OU professors and two postdoctoral fellows has been assembled to execute the project. The principal investigator, Prof. Yu is responsible for providing technical expertise and project management, including planning and coordination, monitoring the progress, and reporting to the program manger. Prof. Xue is in charge of data assimilation, numerical models, and NWP. He has been providing the high-resolution model data to be used for the PAR emulation. Prof. Yeary brings his expertise of adaptive signal processing, Kalman filtering, and clutter filtering to develop optimal scanning strategies. Prof. Palmer has been working on the development of PAR emulators and SA algorithms. Prof. Torres who also holds an adjunct faculty position in ECE is involved in the evaluation and quantification of the impact of the PAR scanning strategies on data assimilation and numerical prediction. Prof. Biggerstaff is strongly engaged in the design and coordination field experiments to exercise and validate the results.

## WORK COMPLETED

The team is complete after the two postdoctoral fellows, Drs. Lei and Teshiba, were successfully recruited on August. The team has been working on the research approaches described in the previous section. The following specific tasks are completed.

(1) A website is now established for the project. The URL is http://arrc.ou.edu/depscor/. The description and highlights of the project are shown. In addition, the project results can be disseminated to a wide range of audience through the website. The website is developed and maintained by Dr. Teshiba.

(2) The concept of BMX is verified using both simulated and real data. BMX is one of the two focus areas in the Technology Innovation research thrust.  It was developed to mitigate the fundamental

limitation of mechanically rotating radar to maximize the scan rate and data quality using phased array radar.

(3) The prototype of the PAR emulator is complete. The current emulator can take in the high-resolution numerical outputs from the Advanced Regional Prediction System (ARPS) model and generate the raw time series data at desirable signal-to-noise ratio. The three spectral moments are then estimated by the autocovariance method.

(4) We completed a new 'truth' simulation of a supercell storm at 100 m horizontal resolution using the latest version of ARPS that is consistent with the updated EnKF package. The data will be used to test the radar emulator and the data I/O between the truth simulation, emulator and the EnKF system. We are working on adding additional capabilities in the EnKF system, to assimilate Phased Array data radial by radial, and make the necessary changes to the model startup procedure and initial time integration scheme to reduce the shock that can be introduced by very frequent data ingest into the model.

**RESULTS**

The feasibility and application of BMX to weather observations are demonstrated using the PAR in Norman, Oklahoma. A 28-degree sector from azimuth 183 degree to 156 degree was scanned using two scanning strategies, the BMX and step scan (SS). SS was devised to probe the same 28-degree sector with 28 discrete beam positions. It is similar to the conventional scanning strategy used in weather radar with a mechanically rotating antenna. The BMX reflectivity is shown on the left panel of Figure 1, while the SS reflectivity is shown on the right panel. It is evident that the gross structures of the reflectivity from both scanning strategies are consistent. Note that the fields from BMX appear to have less spatial fluctuations. It is an indication that BMX estimates have smaller statistical uncertainty and thus is more accurate.

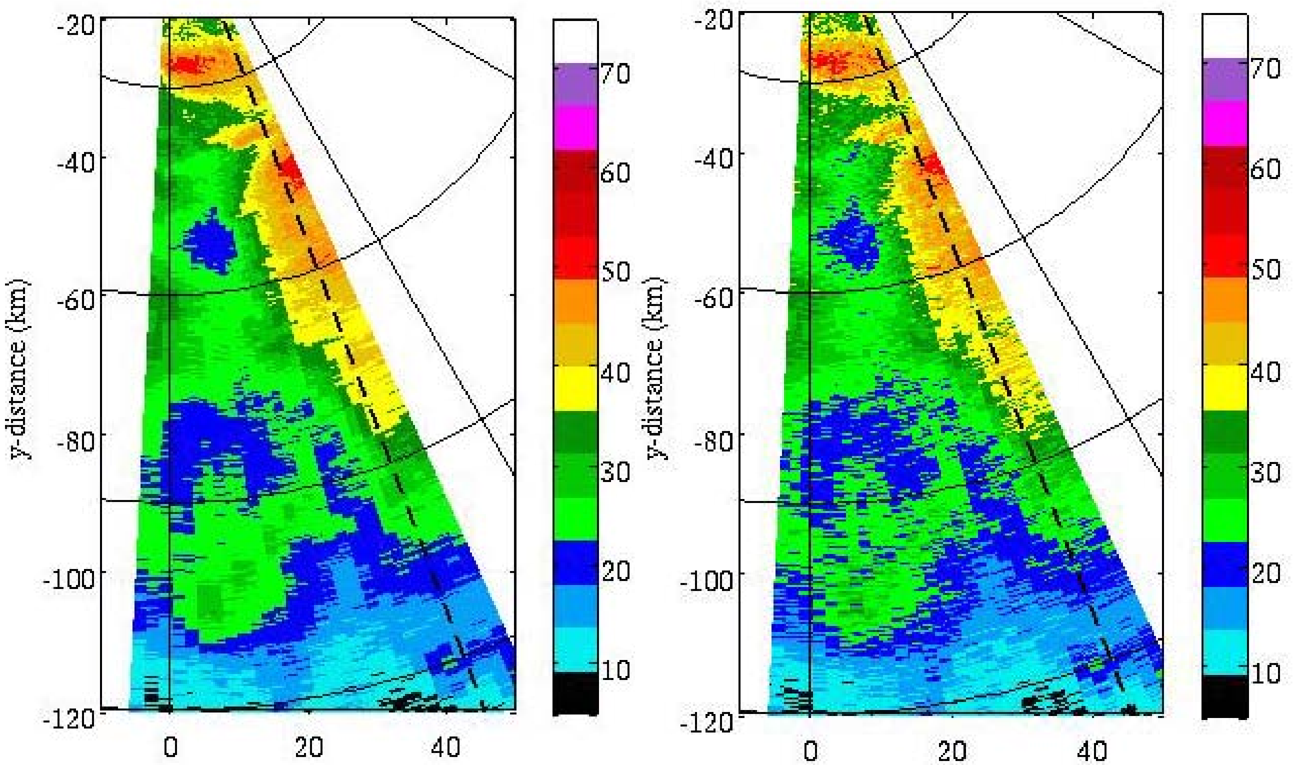


***Figure 1: An example of reflectivity (dBZ) obtained from both BMX (left panel) and SS (right panel) using the PAR in Norman, Oklahoma. It is evident that the fields estimated from both scanning strategies are consistent. In addition, the smaller spatial variations of BMX reflectivity indicate that the quality of BMX estimates is higher.***

Note that the scan time for both BMX and SS are the same in this case. Therefore, the lower statistical error of BMX estimates indicates the improvement in scan time could be obtained using BMX when the estimation accuracy is the same as SS. The two scanning strategies were alternated 50 times in order to obtain the statistical analysis. The improvement factor of scan time is defined such that the same SD is achieved for both BMX and SS. In this experiment with the same scan time, the reduction in SD using BMX can be translated into the improvement factor. The statistical result of this experiment in terms of improvement factor is demonstrated in Figure 2.

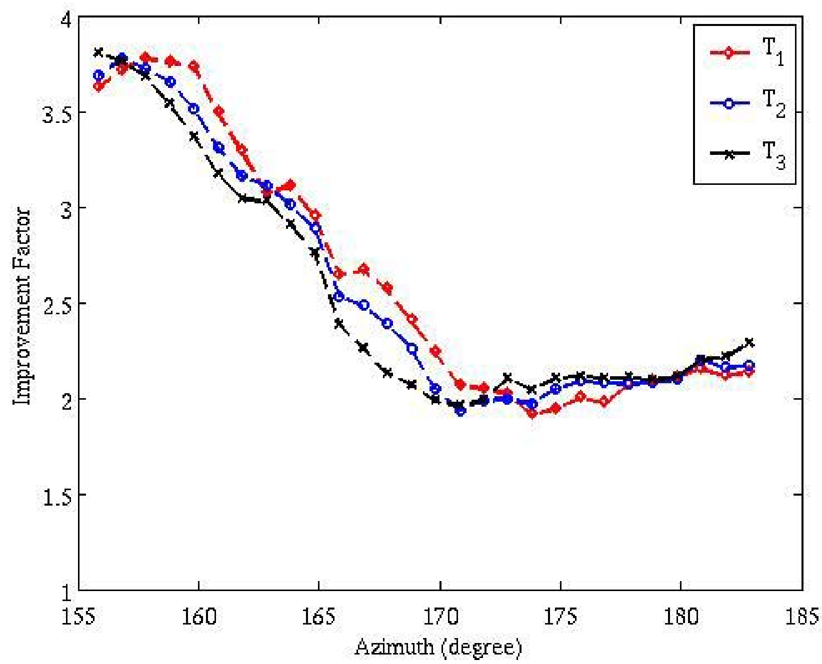


***Figure 2: Average improvement factor of radar scan time at 28 radials in a specially designed PAR experiment. It is shown the scan time can be improved by a factor of 2 to 3.8 using BMX without compromising the statistical accuracy of the measurements.***

The improvement factors from the three time periods of statistical analysis are consistent. It is clear that the scan time can be improved by an average factor of 2-3.8 in this case. Note that the first few radials are associated with high reflectivity regions and, hence estimates therein can be improved more significantly than elsewhere.

Statistical analysis has shown that a new scanning strategy of BMX can provide fields of the three spectral moments that are consistent with those from SS. Moreover, the accuracy of the spectral moment estimates can be higher than those from conventional weather radar for the same scan time. The results indicate that rapid scans can be achieved by BMX and the data quality required by conventional radar is still maintained.

## IMPACT/APPLICATIONS

The novel BMX scanning strategy for the PAR can provide accurate estimate of the weather products more rapidly. In addition, the BMX is designed such that multiple tasks can be performed simultaneously with weather observations. In other words, the weather information can be obtained in a tactical environment in a more efficient manner with minimum interfering battle operations.

## PUBLICATIONS


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